OBSERVATIONS ON THE SEASONAL CHANGES IN TEMPERATURE, SALINITY, PHOSPHATES, AND NITRATE NITROGEN AND OXYGEN OF THE OCEAN WATERS ON THE CONTINENTAL SHELF OFF NEW SOUTH WALES AND THE RELATIONSHIP TO PLANKTON PRODUCTION.

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(Plate xi; eleven Text-figures.)

[Read 25th September, 1935.]

*Introduction.**

In our first paper on the seasonal changes in the plankton off the coast of New South Wales (Dakin and Colefax, 1933) we indicated that little investigation had been made of the biological conditions prevailing throughout the year in Australian coastal waters. The same criticism holds good in regard to physico-chemical studies. In fact, had it not been for the Barrier Reef Expedition of 1928–29 one might have said that no physico-chemical observations extending over even a few months had ever been made round the Australian continent. Surprising as it may seem, it is not easy to discover sea-temperature records for the ocean coastal waters apart from those which have been taken by various ocean-going vessels and reported to the Commonwealth Government. These temperature records have been ably utilized by Mr. G. H. Halligan (Halligan, 1929) in plotting a series of isotherms for the Tasman Sea (S.W. Pacific), and an area of the Indian Ocean off Western Australia. They are all surface records—or of the sub-surface water if the temperatures were taken in the engine room.

The observations to be reported in this paper are the result of a prolonged series of records made in conjunction with a biological investigation at one station situated approximately 3 to 4 miles east of the entrance to Port Jackson, coast of New South Wales. They extend over 3½ years, but reliable nitrate nitrogen analyses were only made during part of the time and certain other tests (oxygen) were made over a still shorter period.

The purpose of the investigation was primarily to discover the conditions under which plankton production took place in our southern waters and also to obtain information regarding any physical conditions which might be correlated with seasonal variation in plankton and the movements of fishes.

Such a survey as ours—concentrating on one station, although other odd records were made not far away (some in deeper water and some closer in-shore)—must be regarded as a preliminary to larger scale ocean investigations. The use of a small auxiliary yacht (Pl. xi, fig. 1), without which our work would

* The pursuit of these marine investigations has been valuably aided by grants from the Research Endowment Fund of the Council for Scientific and Industrial Research, to whom our thanks are tendered.

have been quite impossible, still left us without the means to conduct anything like the seasonal voyages of the investigation vessels employed in similar hydrographical work in the North Sea and English Channel. It is also a pity that our work is so isolated—comparisons with similar observations that might be made to the south off Tasmania and to the north off the Barrier Reef would be distinctly interesting. Notwithstanding the difficulties and limitations, this first work has revealed some interesting facts, more especially since the plankton investigations at the same station are the first in Australasian waters to show a seasonal rhythm akin to that so well known in the Northern Hemisphere (actually the first discovery of spring and autumn phyto-plankton maxima in the Southern Hemisphere).

Technique.

Since the usual oceanographic apparatus has been utilized we shall only comment on any points which have been unusual or which may be helpful to workers placed in a similar position elsewhere.

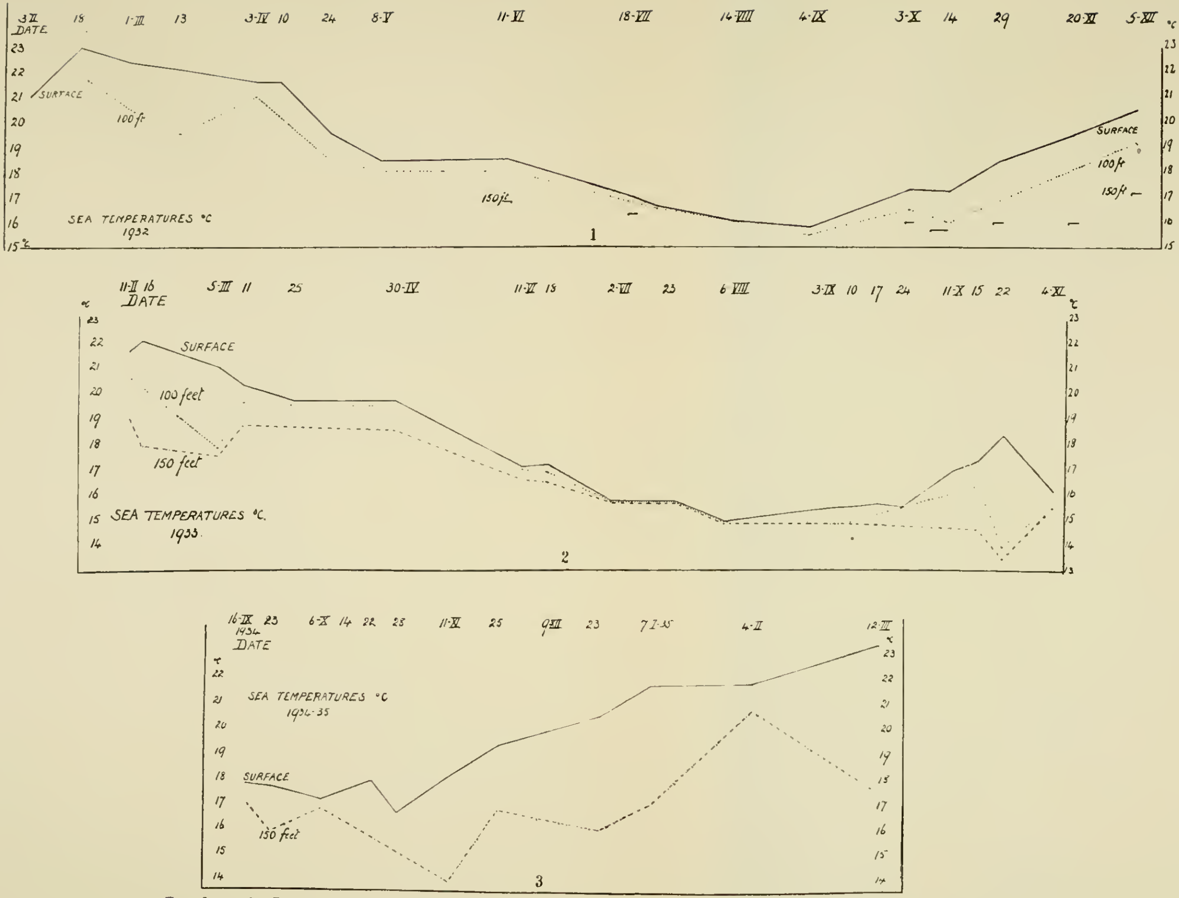
The auxiliary yacht "Thistle" utilized for our work is a strongly built cutter of about 12 tons, length (waterline) 29 feet, beam 11 feet 6 inches, and draft 5 feet. She has a tuck stern—no overhang. She is gaff rigged and is admirably adapted for ocean cruising, except that for more prolonged deep-sea work under bad conditions a smaller cockpit would be desirable if not essential. The auxiliary engine is a 25 h.p. Ailsa Craig, but sails are used whenever possible. The engine is, however, almost always utilized when towing plankton nets horizontally, in order that they will be drawn at uniform and similar speeds on the different occasions.

Considerable difficulty was experienced at the outset in rigging a well known type of meter wheel at the end of a boom, owing to the fact that the movements of the boat in a bad sea were extremely lively (especially when at work but not under way). It was soon found essential to limit the movements of the associated gear so that there were as few freely moving parts as possible. Eventually, with this in view, the boom shown in the photograph (Pl. xi, fig. 2) was constructed. It carries a reel with 100 fathoms of stranded wire, also the recording mechanism of a meter wheel, and in addition a simple mechanism of springs and pulleys to act like the old-fashioned accumulator and counter severe and sudden strains caused by the upward and downward plunges of the vessel. Unfortunately the machine is hand worked. The mechanism could be improved considerably by the addition of a small electric winding motor. The boom is supported on the "forrad" side of the mast on a spider band about one foot above the deck, with a single topping lift and two guy ropes.

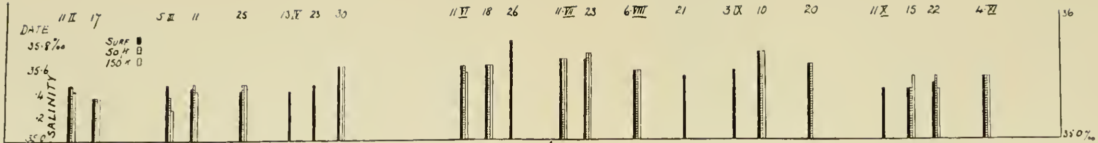
A Lucas sounding machine is mounted as illustrated (Pl. xi, fig. 3), the scaffold of galvanized iron enabling the machine to project slightly overboard and to support it adequately, notwithstanding the lack of bulwarks. It is placed just aft of the shrouds on the starboard side; the boom with the gear referred to above is used on the port side.

The water bottle generally used is the Nansen Petersen, but we also have Ekman reversing bottles, and reversing thermometers are available.

The usual procedure has been to sail out from the harbour of Port Jackson to our station which has been chosen sufficiently far out to be beyond the influence of tidal water emerging from the harbour and sewer outfalls on the coast. The station is fixed by bearings taken with sextant or range finder. At the beginning



Text-figs. 1-3.—Diagrams showing the seasonal variations in the sea temperatures, at depths—surface, 100 feet, 150 feet. 1, during the year 1932; 2, during the year 1933; 3, during the half-year 1934-35.



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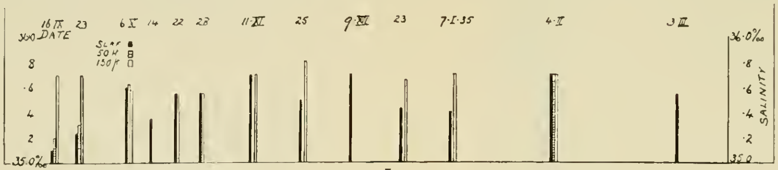

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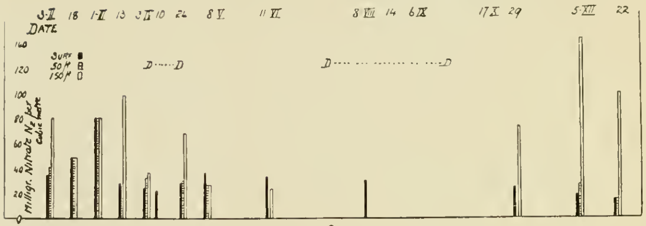

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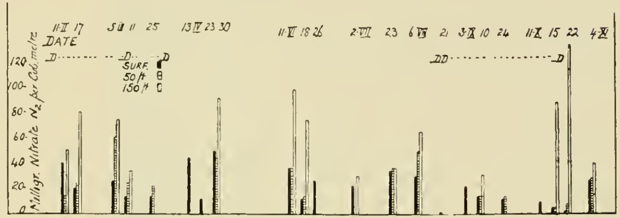

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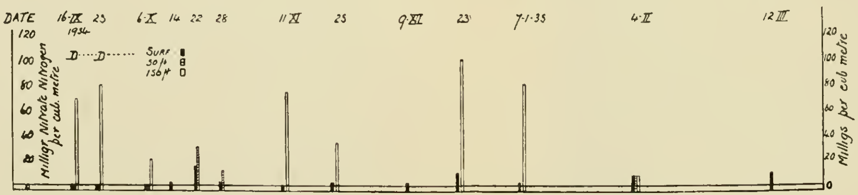

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Text-figs. 4-5.—Diagrams showing seasonal variations in salinity of the sea-water during the year 1933 (fig. 4) and the half-year 1934-35 (fig. 5), at depths—surface, 50 feet, 150 feet.

Text-figs. 6-8.—Diagrams showing seasonal variations in nitrate nitrogen in the sea-water at depths—surface, 50 feet, 150 feet. 6, during the year 1932; 7, during the year 1933; 8, during the half-year 1934-35.

D.......D indicates diatom maxima. The presence of an ordinate column only between the base lines indicates that a sample was taken, of which the nitrate nitrogen content was zero.

of our investigations a sounding was always made before other work was commenced, but later it was found unnecessary as the sea-bottom was of fairly uniform depth in the neighbourhood of our mark and our position could be found satisfactorily. In any case, we could not risk making observations very near the sea-bottom, owing to the usually prevailing swell and the consequent considerable rise and fall of our vessel. It was decided, therefore, to make collections in surface water, 25 feet depth, 50 feet depth, 100 feet depth and 150 feet depth, and at greater depths on the shelf according to plan when making other stations further from the land. The depth at our station was approximately 30 fathoms (54·8 metres).

Water samples were brought back to the shore laboratory for analysis, but pH observations and the preliminary additions of reagents for oxygen determinations (Winkler's method) were carried out at sea.

Notes on Analytical Methods.

The method adopted for phosphate analysis has been the colorimetric method of Déniges as set out by Atkins (1923, 1925, and 1926) using ammonium molybdate solution and stannous chloride in the presence of sulphuric acid.

Nitrate nitrogen has been estimated by the method introduced by Harvey (1928*a*), using a reduced strychnine product in sulphuric acid. At first we had great trouble in applying this analytical method—similar troubles seem to have been met with elsewhere. The difficulty was, however, eventually traced to impurities in the reagents.

During the preparation of the "hydrostrychnine", it was found advisable to heat for periods ranging from 24 to 36 hours, the contents of the flask being carefully shielded from any foreign gases.

An interesting fact that came to light was that a good batch of the reagent could be diluted to an amazing degree with chemically pure sulphuric acid and still retain its sensitivity unimpaired. Thus, in one case, from a litre of hydrostrychnine and sulphuric acid, prepared according to Harvey's directions, no less than four litres of sensitive reagent were made, by the addition of fresh quantities of pure sulphuric acid.

Chlorine has been determined by titration of sea-water with silver nitrate using potassium chromate as indicator according to the plan set out by Oxner and Knudsen (1920). "Normal" sea-water (as used in European laboratories) has, however, not as yet been obtainable. We shall be able to make any small correction later to allow for a fine comparison with results of observers elsewhere. This does not of course seriously affect the main issue—a review of the changes prevailing at our station during the period of observation.

A variation of the usual method of applying Winkler's method for oxygen analysis was developed, which may be of considerable service to other workers faced with our difficulties at sea. We had found at the outset that it was both expensive and inconvenient to try and introduce 0·5 c.c. of 40% manganous chloride solution and 1 c.c. of the concentrated caustic soda-potassium iodide solution into a filled 100 c.c. bottle of sea-water on a very unstable deck. The pipettes were too often broken and the caustic soda spilled about.

To obviate this, small glass bulbs (serum capsules) of the desired capacities were obtained and *filled* with the correct quantities of the reagents by immersing them in the fluids concerned under a bell-jar attached to a vacuum pump. This method made it unnecessary to heat the bulbs or to inject the fluid into them with a fine syringe. The bulbs were next sealed in a blowpipe flame. All that was then necessary was to take boxes of the two sorts of bulbs to sea. The method was as follows: A 200 c.c. glass-stoppered bottle, the capacity of which was exactly known with the stopper inserted, was filled to the brim with sea-water. Two bulbs, one containing manganous chloride, the other caustic soda-pot. iodide solution (according to the usual formula), were next carefully dropped in and smashed at the bottom of the bottle by pressing on them with a glass rod which was then carefully withdrawn. The stopper was inserted, adopting the usual precautions, and the contents well shaken and allowed to stand. The rest of the procedure was carried out in the usual manner for Winkler's test. A great advantage of this method is that it removes any necessity for carrying the caustic soda solution (except in the little phials) and obviates all work with the small pipettes usually necessary and often difficult to keep clean and ready for use at sea.

In commencing our work on the plankton cycle in south-eastern Australian waters, attention has been focussed particularly on the phosphate and nitrate content of the sea-water in view of the conclusions already reached by European workers on the importance of these substances as controllers of plankton production. They are amongst the essential substances for the development and growth of the phytoplankton and they are limited in quantity in the sea; nitrate nitrogen was regarded quite early in plankton investigations as of especial significance in limiting the production of phytoplankton in the sea. Nitrites were tested for on several occasions but. as the amount present was less than 1 mg. per cubic metre in the ocean-water examined, further work was left until the research could be extended to cover other substances not at present investigated.

The differences in hydrogen-ion concentration during the successive visits to our station were all of such a small order as to make the most accurate determinations essential if to be of any use. A continued investigation was therefore left until an electrical method of determination was available.

The Temperature Conditions.

The range of temperature met with at our station is small and on the whole the changes in temperature are both gradual and steady. We are evidently influenced but little by the land, but more elaborate observations are urgently necessary on lines running out from Port Jackson to the edge of the continental shelf. The total annual range of temperature variation of the surface water is only about 7° C. The annual range at a depth of 30 fathoms is less still.

The highest temperatures reached are usually between 22° and 23° Centigrade and occur in February or March. The lowest surface temperatures are to be found in August or September. The range is shown in the graphs (Figs. 1, 2, 3).

It will be noticed that during the winter months the surface temperature at our station differs but little from the temperature at depths of 25, 50 and 150 feet. During the period that the temperature is at its lowest the water between surface and bottom is almost at the same temperature. From the date in spring when the surface waters begin to rise in temperature the difference between surface and bottom becomes more and more pronounced.

These features are all of a well recognized character in other parts of the world. There is quite a definite "layering" in the summer (more perhaps than we expected, considering the turbulence of the seas), and the deeper water attains its maximum later than the surface water.

But it is clear that before drawing any further conclusions, many more data are essential and there should be a chain of stations from the land to the edge of the continental shelf. We prefer, therefore, merely to set out the facts covering the temperature conditions observed in order to make known the general prevailing conditions for correlation with our biological data. The data given are, however, sufficient to indicate one important factor in connection with the nitrate and phosphate content of the water. The conditions in summer will hinder any rapid regeneration of nitrate and phosphate supplies if these substances are exhausted in the surface waters by the activity of the plankton. The pronounced "layering" will tend to prevent supplies passing upwards from the sea bottom. On the coastal shelf, however, as at our station, abnormal weather conditions may bring about a temporary destruction of the summer conditions, as indicated on Figure 3 for February 4, 1935.

The range of sea temperatures within the harbour of Port Jackson is of course far greater than at our offshore station and variations between 12·3° C. and 27° C. have been noted.

Salinities.

Chlorine analyses have been made on samples taken at our station over a period of three years. Some of these results are plotted in Figure 5. There is no reason to depict or tabulate the full three years' work.

The water off our coast is of an average salinity of approximately 35·5‰. This corresponds to the "general" ocean salinity that may be expected in 30° latitude. It might, however, be regarded as a high salinity for coastal waters. In this connection it must be remembered that, normally, relatively little fresh water enters the sea from Port Jackson (except after heavy rains) and we have deliberately avoided that area which might be expected to be swept by currents from the harbour at ebb tide.

If we take the surface water and the water at 150 feet depth for comparison, it is apparently just as likely for the salinity to be the same throughout, or for the surface salinity to be greater, or less than that of the deeper layer. These differences are, however, rarely greater than 0·3‰, and usually less (see figs. 4 and 5).

Throughout the year there is a slight fluctuation in the salinities, but it is neither large nor regular and, so far, we have not been able to correlate the very small "ups and downs" with changes in the weather or with heavy rains. The range is too small, as, for example, 35·46‰ February 11 to 35·36‰ a week later, then from 35·46‰ to 35·40‰ between March 5 and April 13, when a slight increase led up to 35·60‰ on April 30. A salinity of 35·8‰ was recorded on June 26. The extremes for the surface in 1933 were 35·80‰ and 35·36‰. There is some indication that the salinity of the deeper water is more constant than that at the surface. This might well be expected. Probably most of the small changes are due to complex tidal currents in proximity to the coast and it seems just as likely that if we had been making successive daily observations we should have met with variations of similar degree in close succession, even on adjacent days.

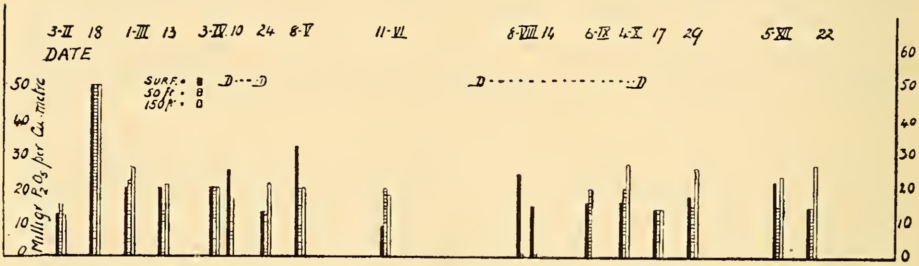
So far, then, we can take it that no seasonal rhythm has made itself apparent, and that the water at our station preserves the salinity of ocean water.

Phosphate.

In view of the fact that phosphate is regarded as one of the essential foodstuffs of the phytoplankton, its mean quantity and its seasonal variation in our waters is of considerable importance.

The data given in the figures and tables cover the period from February 3, 1932, to November 4, 1933, and from September 17, 1934, to March, 1935. Unfortunately, owing to difficulties in obtaining a crew during the summer vacations, the summer months of the season 1932–33 (December to January) and 1933–34 presented many lacunae. These unavoidable gaps were covered by a special effort made to run weekly or fortnightly cruises between September, 1934, and March, 1935. This sequence was one of our most successful, and threw considerable light on the chemical conditions of the offshore waters during the summer.

The first point that strikes one on glancing at the graphs (Figures 9, 10, 11) is that the phosphate content is on the whole very stable during the year. There



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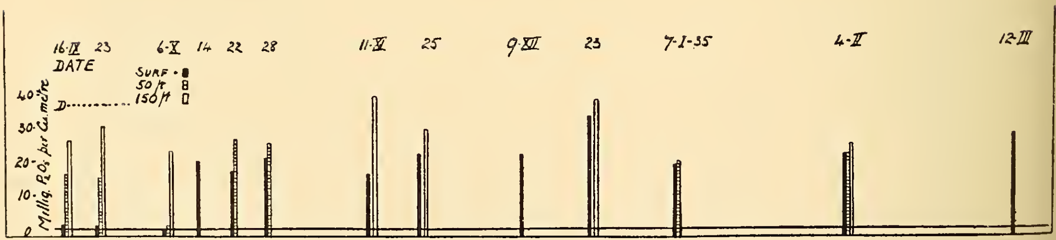

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Text-figs. 9-11.—Diagrams showing seasonal variations in Phosphate at depths—surface, 50 feet, and 150 feet.

Fig. 9, during the year 1932; Fig. 10, during the year 1933; Fig. 11, during the half-year 1934-35.

The presence of an ordinate column only between the base lines indicates that a sample was taken, of which the phosphate content was zero.

(D......D), diatom maxima.

are ups and downs, but the average during the summer months is not appreciably less than during the winter months, and at the surface it varies between say 15 and 25 milligrams of P_2O_5 per cubic metre.

As these are the first phosphate determinations to be made regularly in the coastal waters of south-eastern Australia, it is particularly interesting to make a comparison with other areas of the sea where the phosphate content is now fairly well known.

According to Harvey (1928*a*) the surface water of the English Channel is at its maximum during the months from October to March inclusive, the amount being roughly 30 mg. P_2O_5 per cubic metre. In the summer months (May to September), however, there is a great fall in the phosphate content, and the amount goes down almost to zero—varying between 0 and 8 mg.

In the cold waters of the Antarctic (Hart, 1934) the phosphate in the surface waters also suffers a depletion during the phytoplankton season, but the total never goes below 50 mg. P_2O_5 per cubic metre, which is twice our average amount. On the other hand, well over 100 mg. per cubic metre is frequently recorded.

As a result of the Great Barrier Reef Expedition of 1928–29, there are records (Orr, 1933) for phosphates in the Barrier Reef Lagoon waters which are exceedingly interesting for comparison with ours. The quantity of phosphate was relatively uniform, but only about 5 mg. per cubic metre. It was rare for it to reach 8 mg. per cubic metre, and 14 mg. per cubic metre at 28 metres depth was regarded as so high a value as to be due to contamination and not a true record. Unfortunately, few observations were made in the open sea, but those seaward of the reefs showed just as low figures in the surface waters.

On the whole, therefore, our coastal water approximates more to the English Channel conditions, but without the exhaustion of P_2O_5 in the summer—in other words, a seasonal cycle is not pronounced. It is worthy of note that Atkins' analyses (1926) of waters collected in the open Pacific Ocean between the Galapagos and the Marquesas (in latitude 0° to 8° S.) showed contents between 5 and 27 mg. with the average of 18 mg. for 5 samples.

When, however, we look more closely into the details of the tables, we find variations of importance, even though they be of short duration. On certain dates the phosphate content of the surface water went down to zero or to a mere trace. These dates were April 13, 1933, September 3, 1933, and October 15 and 22, 1933 (see fig. 10). The phosphate content was down to zero again on September 16 and 23, and October 6, 1934 (see fig. 11), which means that it was practically absent during the whole month of September and the first week of October (see Tables I and II).

An inspection of the plankton catches for the dates mentioned provided a striking confirmation of the theories put forward in Europe to explain the variation in nitrate and phosphate content of the surface waters of the sea during the year. They showed that the phosphate content of the sea off our coast never went down to zero without there being an unusual (for this place) development of diatoms.

As a matter of fact the taking of the summer series of observations 1934–35 (Table II) was entirely unpremeditated and was initiated as a result of finding no nitrate and no phosphate in a sample of water, on September 17, 1934, which had been collected for bacteriological examination. This result was so surprising that the boat was immediately taken out again with fine plankton nets. It was

TABLE I.—*Composition of the Ocean Water from N.S.W. Coastal Shelf.*
Phosphates. 1933.

Depths. (Metres.)	Dates.																				
	Feb.		Mar.			Apr.		June.			July.		Aug.		Sept.			Oct.			Nov.
	11	17	5	11	25	13	23	11	18	26	2	23	6	21	3	10	24	11	15	23	4
Surface	19	14	16	10	13	0	tr.	20	20	15	19	16	21	14	21	tr.	17	11	tr.	tr.	18
15·2..	19	11	19	13	13	—	—	21	20	—	—	18	23	—	—	19	17	—	13	18	18
30·5..	21	14	22	18	14	—	—	23	25	—	—	19	22	—	—	22	—	—	13	43	18
45·7..	25	20	—	20	—	—	—	31	27	—	36	16	23	—	—	21	—	—	28	39	25
61	—	22	—	—	—	—	—	—	—	—	—	—	—	—	—	—	—	—	—	—	—

The figures indicate milligrams of P_2O_5 per cubic metre.

In this and following tables, where no figure is given no sample was taken.

TABLE II.—*Composition of the Ocean Water from N.S.W. Coastal Shelf.*
Phosphates. 1934–1935.

Depths. (Metres.)	Dates.												
	Sept.		Oct.				Nov.		Dec.		Jan.	Feb.	Mar.
	16	23	6	14	22	28	11	25	9	23	7	4	12
Surface ..	tr.	tr.	0	20	17	21	16	22	22	33	19	22	27
15·2 ..	16	15	tr.	—	26	25	—	—	—	—	20	22	—
30·5 ..	—	—	—	—	—	—	—	27	—	35	28	22	31
45·7 ..	26	30	23	—	—	—	39	29	—	38	—	25	—

discovered that the sea was thick with phytoplankton. In fact the catches were as big as any ever taken by us in these waters. The occasion provided such a remarkable demonstration of the relationship of phytoplankton to the quantity of phosphates and nitrates in the water that it was decided to make a special effort to continue the water analyses, notwithstanding possible bad weather, and to follow up the return of the chemical substances in question. A detailed picture of the water at our station during the summer months 1934–35 was the result. Notwithstanding, however, the fact that a large outburst of phytoplankton reproduction will bring down the phosphate content of our coastal waters to zero, this condition does not continue for the long season noted in British waters. On the occasions noted above in 1933, when the phosphate in the surface waters was reduced to a trace, it was back again ten days or so afterwards. After the spring diatom maximum in September, 1934, the phosphates were down to zero for about three weeks. Regeneration from deeper waters then resulted in the amount rising to 20 mg. per cubic metre, and this figure was kept up during the summer.